

IMPROVEMENT OF DISTRIBUTION TRANSFORMER FAULT ANALYSIS USING  
FRA METHOD

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## ABSTRACT

The distribution transformers are one of the most expensive components in the electrical power distribution system. During its lifetime, distribution transformers are exposed to several failures. For this reason, it is crucial to continuously monitor its condition. Frequency Response Analysis (FRA) is an advanced electrical test, which is commonly employed to investigate the transformer's main winding. Moreover, it has been shown to be sensitive to non-mechanical changes such as winding insulation. The measured FRA result needs to be compared with the previous measurement to identify any variation between them. The variation will indicate mechanical changes in the transformer. However, interpreting the variation to determine the type, location, and severity of the suspected failure, requires expertise. For this reason, further understanding of the damage detecting characteristic of FRA is required. In this study, an electrical circuit model is developed based on 33/11kV, 1MVA distribution transformer to investigate the influence of various changes in the winding RLC values on the frequency response. The model is also used to simulate other failures such as winding deformation, bushing and short circuit faults. In addition, the tap changer fault and weakness of clamping structure are also investigated by examining an 11/0.433 kV, 500KVA distribution transformer. Additionally, the transformer ageing and degradation of winding's insulation is also investigated using different FRA measurement configuration. Findings show that tap changer coking and clamping faults affect the frequency response at less than 2kHz. FRA capacitive inter-winding shows isolation in between 2kHz to 20kHz due to transformer ageing. The frequency response shifting towards lower frequencies at 20kHz to 2MHz due to winding insulation degradation. Also, in this study, the method or interpretation scheme for FRA is obtained. It is a guideline in the form of a flowchart, which is proposed for the first time and helps the engineers in having a better interpretation of FRA results. In conclusion, this study is to improve the understanding on the distribution transformers faults detection using FRA method.

## ABSTRAK

Pengubah kuasa adalah salah satu komponen yang paling mahal dalam sistem kuasa elektrik. Semasa kitaran hayatnya, pengubah kuasa terdedah kepada beberapa kegagalan. Olehsebab itu, adalah sangatpenting untuk memantau keadaan pengubah kuasa secara berterusan. Analisis sambutan frekuensi (FRA) adalah ujian elektrik lanjut yang biasa digunakan untuk mengenal pasti belitan utama di dalam pengubah kuasa. Selain itu, ia telah terbukti sensitif terhadap perubahan bukan mekanikal iaitu pada penebatan di dalam pengubah kuasa. Pengukuran FRA yang dibuat perlu dibandingkan dengan pengukuran yang sebelumnya untuk mengenal pasti sekiranya terdapat sebarang variasi di antara kedua-dua. Variasi antara dua pengukuran akan menunjukkan bahawa terdapat perubahan mekanikal yang berlaku dalam pengubah. Walau bagaimanapun, kepakaran seseorang diperlukan untuk mentafsir variasi ini dalam menentukan jenis, lokasi, dan tahap kegagalan yang dikesan. Oleh yang demikian, pemahaman yang lebih lanjut mengenai ciri-ciri FRA untuk mengesan kerosakan adalah diperlukan. Dalam kajian ini, model litar elektrik dibangunkan berdasarkan 33 / 11kV, 1MVA pengubah pengedaran untuk mengkaji kesan terhadap kepelbagaian RLC perubahan dalam belitan pada sambutan frekuensi. Model ini juga digunakan untuk membuat simulasi kesalahan litar pintas pada belitan pengubah. Tambahan pula, kegagalan pada penukar sadap dan kelemahan struktur pengapitan juga dikaji dengan memeriksa pengubah agihan pada 11/0.433 kV, 500KVA. Tambahan pula, penurunan kepada kualiti penebatan belitan juga dikaji menggunakan FRA. Hasil kajian menunjukkan bahawa Kesalahan coking dan penjepit menjejaskan tindak balas frekuensi kurang daripada 2 kHz. FRA antara penggulangan menunjukkan pengasingan di antara 2kHz hingga 20kHz disebabkan penuaan pengubah. Tindak balas kekerapan beralih ke frekuensi yang lebih rendah pada 20kHz hingga 2MHz disebabkan penggulangan penebat penggulangan. Kajian ini juga mencadangkan kaedah atau cara penafsiran FRA. Ia adalah garis panduan dalam bentuk carta alir yang membantu para jurutera ke arah menafsirkan pengukuran FRA yang lebih baik. Kesimpulannya, kajian ini adalah untuk



meningkatkan pemahaman tentang pengesanan kesalahan transformer pengedaran menggunakan FRA.



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## LIST OF SYMBOLS AND ABBREVIATIONS

Cd	Capacitance between discs
Cg	Capacitance to ground
Ct	Capacitance between turns
D1	Disc number 1
h	Height
Mij	Mutual inductance
Mt	Number of turns per disc
N	Number of discs
Gs	Self Conductance
Ls	Series Inductance
$\sigma$	Standard deviation
Cs	Series Capacitance
Rs	Series Resistance
Dyn11	Transformer connection in Delta-Star to natural
tp	Winding insulation thickness
w	Width
ABB	ASEA Brown Boveri (heavy electrical equipment factory)
ASLE	Absolute Sum of Logarithmic Error
CC	Correlation Coefficient
CSD	Computer Standard Deviation
DETC	De-Energized Tap Changer
DGA	Dissolved Gas Analysis
DIP	Digital Image Processing based technique
DRM	Dynamic Resistance Measurement
EMF	Electromagnetic Force
EWT	EPE Wilson Transformer
FEM	Finite Element Method
FRA	Frequency Response Analysis

HV	High Voltage
HF	High Frequency Region
HVAC	High Voltage Alternating Current
HVDC	High-voltage Direct Current
HV-LV	High-voltage and Low-voltage
IEC	International Electro technical Commission
IFRA	Impulse Frequency Response Analysis
KVA	kilo-Volt-Amperes
LF	Lower Frequency Region
LV	Low Voltage
LVI	Low Voltage Impulse
LTC	Load Tap Changer
MF	Middle Frequency Region
MM	Minimum–maximum ratio
MTL	Multi-conductor Transmission Line
MTM	Malaysia Transformer Manufactures
OLTC	On-Load Tap Changer
PCC	Parametric Counterpart of Pearson CC
RLC	Resistance, Inductance, and Capacitance
SVM	Support Vector Machine
SCC	Spearman Correlation Coefficient
SD	Standard Deviation
SCI	Short Circuit Impedance
SVM	Support Vector Machine
SSE	Sum Square Error
SSMMRE	Sum Square Maximum Minimum Root Error
SSRE	Sum Square Root Error
TF	Transfer Function
TNBR	Tenaga National Berhad Research
TTR	Transformer Turn Ratio
WR	Winding Resistance
WSR	Wilcoxon Signal Rank



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**PTTA UTHM**  
PERPUSTAKAAN TUNKU TUN AMINAH

# CHAPTER 1

## INTRODUCTION

### 1.1 Research background

The increasing electricity demand, in developing countries, requires a significant improvement in the power distribution system, especially in the distribution transformers. It is well-known that distribution transformers are one of the most important components in the electrical distribution network [1]. The main function of a distribution transformer is to step down voltages. For commercial or domestic use of electricity, the distribution transformer steps down the voltage to the desired level. Hence, when the distribution transformer is operating at an extremely high load, to meet the demands, it is subjected to failures or accelerated ageing. This could be due to an increase in mechanical, electrical, and thermal stresses.

There are other failure modes such as dielectric and physical chemistry. Roizman *et al.* in [2] shows various failure modes from about 211 substations. The failure modes and its percentages are shown in Figure 1.1. In addition, other accidental faults could occur such as faults occurring: mishandling, shown in Figure 1.2(a); due to earthquakes, shown in Figure 1.2(b); due to lightning strikes, shown in Figure 1.2(c); and even due to explosion of combustible gases accumulating in the transformer oil, shown in Figure 1.2(d) [3, 4]. The mishandling of the transformer during delivery could cause serious damage to the winding and the core [5]. Earthquakes could also cause a serious failure such as winding displacement. The transient overvoltage generated by lightning strikes is also a major risk factor which could cause winding bushing faults. The gas explosion is also a common fault that

can be seen in transformers. In Malaysia, lightning strikes and increases of temperature due to thermal stress are the common causes of the distribution transformer failures [6, 7].

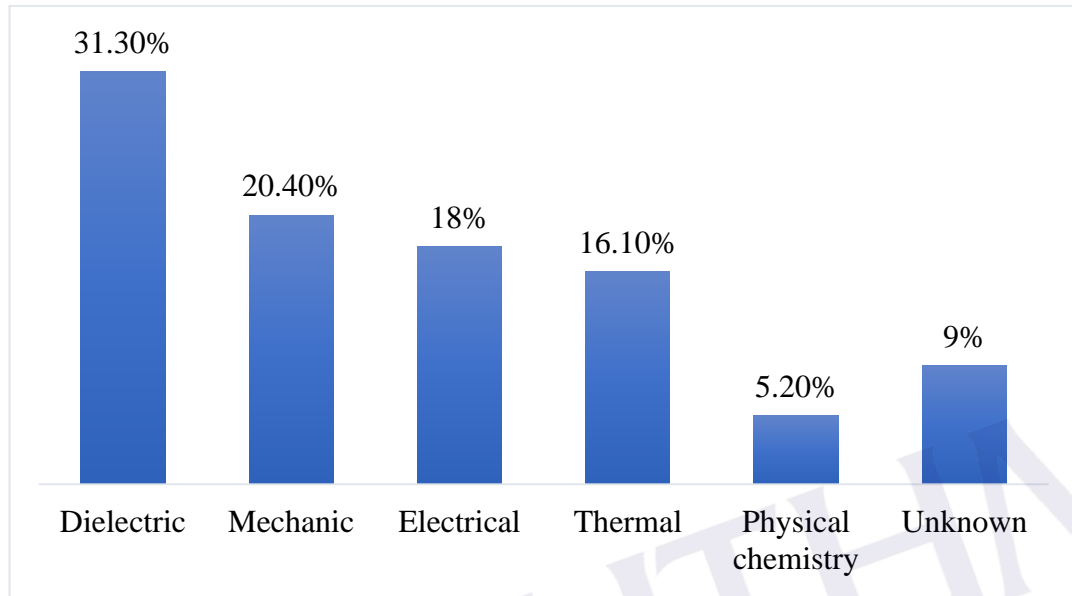


Figure 1.1: Failure modes and its percentage in transformers [2]

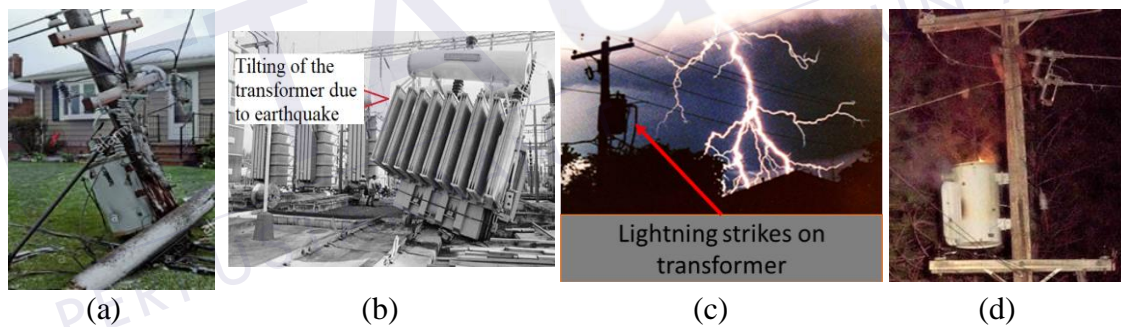


Figure 1.2: Accidental faults occurred on the transformer (a) mishandling (b) earthquakes, (c) lightning strikes (d) gas explosion

These accidental faults could cause insulation degradation, clamping pressure losses, winding deformation, and other detectable failures. These failures reduce the ability of the distribution transformer to withstand the short circuit faults. Therefore, it is required to monitor the transformer condition continually to avoid sudden failures. This is also required because repairing transformer failures contributes to a financial loss. Replacement or repair of failed transformers is also presented by Walters in [8]. It is concluded that the transformer can be fixed for \$54,355 or less. Hence, a well-used diagnostic technique is required to monitor the health condition of the transformer [9].

There are different methods have been proposed to monitor the transformer condition. The Insulating Oil Analysis can provide you with considerable information regarding the current state of the transformer and its remaining lifetime [10]. Dynamic resistance measurement (DRM) is common to check for issues regarding the winding and OLTC. It investigates the resistance of each subsequent tap position and compares it with the reference measurement data of the manufacturers. It is accepted in the diagnosis the condition of On-Load Tap Changer (OLTC) [11, 12]. Another method is called the Transformer Turns Ratio (TTR) test. TTR measurements are performed to verify the fundamental operating principle of a power transformer. By measuring the ratio and phase angle from one winding to the other, open circuits and shorted turns can be detected. It is a well-known technique to detect the condition of winding insulation and winding displacement [13]. Exciting current measurements can also be used to assess the turn-to-turn insulation of the windings, the magnetic circuit of a transformer as well as the tap changer. Short-circuit impedance measurements are sensitive methods to assess possible deformation or displacement of windings. Severe during transportation of the power transformer may cause the windings to move or become deformed. In events like these, short-circuit impedance tests are recommended. Partial discharge (PD) can damage insulation materials in power transformer bushings and windings. This can lead to their failure and costly outages. PD is observed in power transformer bushings and windings insulation material condition assessment. But it is difficult to determine the winding deformation by this conventional test of ratio, impedance, and inductance.

On the other hand, Frequency Response Analysis (FRA) is an advanced method used to evaluate the transformer's internal mechanical faults. The first time FRA was applied on transformers was in Poland in 1966. The measurement technique utilised a Low Voltage Impulse LVI. Then, the method separated and refined in Britain, and the United States. The LVI method is also known as the Impulse Frequency Response Analysis (IFRA) [14, 15]. This non-intrusive test measures the transfer function response of the transformer winding over a wide frequency range (20 Hz to 2 MHz). Earlier, Firoozi *et.al.* in [16] mentioned that the FRA technique still is not widely used due to some limitations. For instance, a lack of availability of correlation between the signature and the changes in the parameter of the equipment. It means that the success of this method relies on the correct

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## APPENDIX A

## LIST OF PUBLICATIONS

- I. S. Al-Ameri, M.F. M. Yousof H. Ahmad, M. Alsubari, M.A. Talib, "Examining faulty transformer tap changer using frequency response analysis", *2017 Int. Symp. Electr. Insul. Mater.*, pp. 259–262, 2017. Published in IEEE explorer library
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- IV. S. Al-Ameri, M. F. M. Yousof, Norhafiz Azis, S. Avinash , M. A. Talib, Ali. A. Salem, "Modelling Frequency Response of Transformer Winding to Investigate the Influence of RLC", *Indonesian Journal of Electrical Engineering and Computer Science, ICED2018*, published in 2019. ISSN: 25024760, 25024752 (Scopus Q3)
- V. S. Al-Ameri, M. F. M. Yousof, H. Ahmad, M. A. Talib. "Frequency Response Analysis For Power Transformer Tap Changer Damage Detection", *International Journal of Power Electronics and Drive Systems (IJPEDS)* ISSN: 20888694 (Scopus Q2 in Electrical and Electronic Engineering).

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